

Stars, gas and dust in elliptical galaxies

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Abstract I will present recent theoretical results on the formation and the high redshift assembly of spheroids. These findings have been obtained by utilising different and complementary techniques: chemodynamical models offer great insight in the radial abundance gradients in the stars; while state semi-analytic codes implementing a detailed treatment of the chemical evolution allow an exploration of the role of the galactic mass in shaping many observed relations. The results will be shown by following the path represented by the evolution of the mass-metallicity relation in stars, gas and dust. I will show how, under a few sensible assumptions, it is possible to reproduce a large number of observables ranging from the Xrays to the Infrared. By comparing model predictions with observations, we derive a picture of galaxy formation in which the higher is the mass of the galaxy, the shorter are the infall and the star formation timescales. Therefore, the stellar component of the most massive and luminous galaxies might attain a metallicity $Z \geq Z_{\odot}$ in only 0.5 Gyr. Each galaxy is created outside-in, i.e. the outermost regions accrete gas, form stars and develop a galactic wind very quickly, compared to the central core in which the star formation can last up to ~ 1.3 Gyr.

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0.1 Introduction

Any model of galaxy evolution presented so far had to overcome the strong challenge represented by the observational fact that elliptical galaxies show a remarkable uniformity in their photometric and chemical properties, one of the strongest constraints being the mass-metallicity relation (e.g. Carollo et al. 1993, Davies et al. 1993). The first proposed scenario of elliptical formation was the so-called monolithic collapse scenario (e.g. Larson, 1974). In this framework, ellipticals are assumed to have formed at high redshift as a result of a rapid collapse of a gas cloud. This gas is then rapidly converted into stars by means of a very strong burst, followed by a galactic wind powered by the energy injected into the interstellar medium (ISM) by supernovae (SNe) and stellar winds. The wind carries out the residual gas from the galaxies, thus inhibiting further star formation. In this way the mass-metallicity (i.e. more massive a galaxies have the higher metal content in stars and gas) relation could be easily explained in terms of metallicity sequences, namely the more massive objects develop the wind later (due to their deeper potential wells) and, thus, have more time to enrich their stellar generations. This scenario has been recently reviewed and modified by Pipino & Matteucci (2004, PM04) in order to take into account that ellipticals show an increasing Mg/Fe abundance ratio in the stars as a function of galactic mass (Faber et al. 1992). Due to the different nucleosynthesis leading to the production of Mg (by type II SNe, on short timescales) and Fe (by type Ia SNe, on longer timescale), the Mg/Fe-mass relation implies that the more massive objects should have formed faster than the less massive ones (see Matteucci, this book, and references therein). Pipino & Matteucci (2004) implemented an infall term in the chemical evolution equation in order to simulate the creation of galaxies and found that most of the photo-chemical observables, including the Mg/Fe-mass relation can be reproduced in a scenario in which the more massive galaxies formed faster and with a much more efficient star formation process with respect to the low mass objects.

PM04 suggested that a single galaxy should form outside-in, namely the outermost regions form earlier and faster with respect to the central parts. A natural consequence of this model and of the time-delay between the production of Fe and that of Mg is that the mean [Mg/Fe] abundance ratio in the stars should increase with radius. Pipino et al. (2006, PMC06) compared PM04 best model results with the very recent observations for the galaxy NGC 4697 (Mendez et al. 2005), and found them in excellent agreement.

Metallicity gradients, in fact, are characteristic of the stellar populations inside elliptical galaxies. Evidences come from the increase of line-strength indices (e.g. Carollo et al., 1993; Davies et al., 1993; Trager et al., 2000) and the reddening of the colours (e.g. Peletier et al. 1990) towards the centre of the galaxies. The study of such gradients provide insights into the mechanism of galaxy formation, particularly on the duration of the chemical enrichment process at each radius. Metallicity indices, in fact, contain information on the

chemical composition and the age of the simple stellar populations (SSPs) inhabiting a given galactic zone.

0.2 The model

The chemical code adopted here is described in full detail in PM04 and PMC06, where we address the reader for more details. This model is characterized by: Salpeter (1955) IMF, Thielemann et al. (1996) yields for massive stars, Nomoto et al. (1997) yields for type Ia SNe and van den Hoek & Groenewegen (1997) yields for low- and intermediate-mass stars (the case with η_{AGB} varying with metallicity). Here we present our analysis of a $\sim 10^{11} M_{\odot}$ galaxy (PM04 model IIb), considered representative of a typical elliptical, unless otherwise stated.

The model assumes that the galaxy assembles by merging of gaseous lumps (infall) on a short timescale and suffers a strong star burst which injects into the interstellar medium a large amount of energy able to trigger a galactic wind, occurring at different times at different radii. After the development of the wind, the star formation is assumed to stop and the galaxy evolves passively with continuous mass loss.

0.3 Results and discussion

0.3.1 The mass-metallicity relation evolution

From the comparison between our model predictions (Fig. 1) and the observed stellar metallicity distribution diagrams derived at different radii by Harris & Harris (2002, see their fig. 18) for the elliptical galaxy NGC 5128, we can derive some general considerations. The qualitative agreement is remarkable: we can explain the slow rise in the $[Z/H]$ -distribution as the effect of the infall, whereas the sharp truncation at high metallicities is the first direct evidence of a sudden and strong wind which stopped the star formation. The suggested outside-in formation process reflects in a more asymmetric shape of the stellar metallicity distribution diagram at larger radii, where the galactic wind occurs earlier (i.e. closer to the peak of the star formation rate), with respect to the galactic centre.

From a quantitative point of view, properties such as the stellar metallicity distribution of the composite stellar populations (CSPs) inhabiting the galactic core, allow us to study the build-up of mass-metallicity relation, which is typically inferred from the spectra taken at ~ 0.1 effective radius. In Fig. 2 we plot the time evolution of the mass-metallicity relation in stars (which reflect the average chemical enrichment of the galactic core as seen at the present day; dashed line) and in the gas (which, instead, is closer to the composition of the youngest SSP, thus being more indicative of a high redshift object; solid line). The mean Fe abundance in the stellar component can reach the solar value in only 0.5 Gyr, making ellipticals among the most metal-rich objects of the

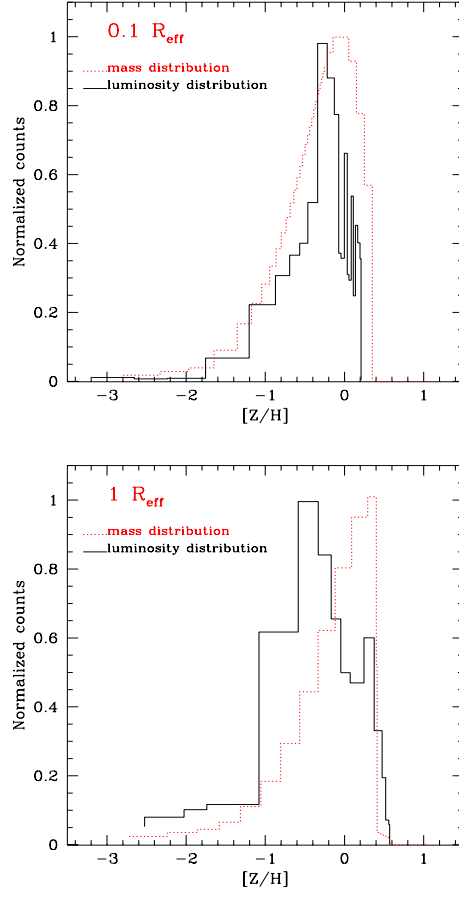


Figure 1: Stellar metallicity distribution distributions for $[Z/H]$ in luminosity (solid line) and mass (dotted line). *Upper panel*: values at $0.1R_{eff}$. *Lower panel*: values at $1R_{eff}$. The plots are presented in the same scale in order to better appreciate the differences among the different distributions.

universe. For the star formation histories of these objects see Matteucci (this book). For the metals locked-up in dust we refer the reader to Calura, Pipino & Matteucci (2007) and Calura (??, this book).

It is intriguing that the Lyman-Break Galaxies observed by Verma et al. (2007) at a redshift of 5 have assembled probably less than 1/10 of their final mass in stars (at a rate of $\sim 40M_{\odot}/\text{yr}$), they have an average age which is lower than 100 Myr and an inferred gas metallicity below $Z = 0.01 Z_{\odot}$. Their finding is in remarkable agreement with our expectations for a present-day elliptical caught in the act of the build-up of the low-metallicity tail of the stellar metallicity distribution curve at very high redshift.

On the other hand, at variance with the stellar metallicity distribution diagrams as a function of $[Z/H]$ (and $[Fe/H]$), abundance ratios such as $[\alpha/Fe]$ have narrow and almost symmetric distributions. This means that, also from a mathematical point of view, the $[< \alpha/Fe >]$ ratio are representative of the whole CSP (PMC06). The robustness of the $[\alpha/Fe]$ ratios as constraints for the galactic formation history is testified by the fact that $[< \alpha/Fe >] \simeq [< \alpha/Fe >_V]$, having very similar distributions. In particular, we find that the skewness parameter is much larger for the $[Z/H]$ and $[Fe/H]$ distributions than for the case of the $[\alpha/Fe]$ one, by more than one order of magnitude. Moreover, the asymmetry increases going to large radii (see Fig. 1, lower panel), up to a factor of ~ 7 with respect to the inner regions. Therefore, it is not surprising that the $[< Z/H >]$ value does not represent the galaxy at large radii, and hence, we stress that care should be taken when one wants to infer the real abundances of the stellar components for a galaxy by comparing the observed indices (related to a CSP) with the theoretical ones (predicted for a SSP). Only the comparison based on the $[< \alpha/Fe >]$ ratios seems to be robust.

Another possible source of discrepancies is the fact that luminosity-weighted averages (which are more closely related to the observed indices) and mass-weighted averages (which represent the real distributions of the chemical elements in the stellar populations) might differ more in the most external zones of the galaxy (compare the panels in Fig. 1). All these considerations result in the fact that the chemical abundance pattern used by modellers to build their SSPs, might not necessary reflect the real trends. Therefore, the interpretation of line strength indices in terms of abundances, can be seriously flawed (see PMC06 for further details). We refer to Pipino et al. (2007b, see also ??, this book) where, the build-up of the metallicity gradients is thoroughly studied.

0.3.2 Globular cluster systems in ellipticals: a different point of view

The analysis of the radial variation in the CSPs inhabiting elliptical galaxies seems to be promising as a powerful tool to study ellipticals. Pipino, Puzia & Matteucci (2007), make use of the stellar metallicity distributions predicted by PMC06 to explain the multimodality in the globular cluster (GC) metallicity

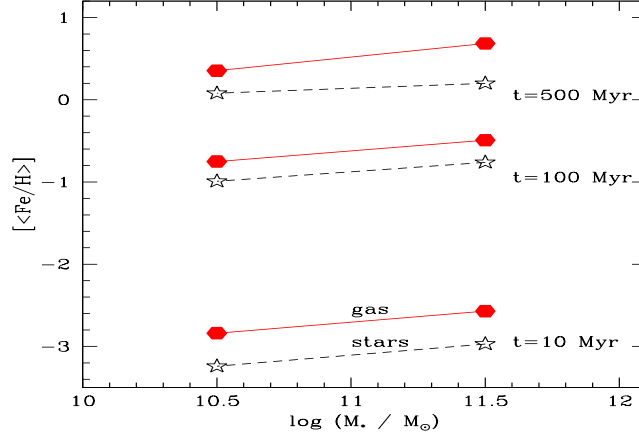


Figure 2: The temporal evolution of mass-metallicity relation for the two studied galactic components (stars and gas).

distribution as well as their high α enhancement (Puzia et al. 2006, P06). In particular, they show that the GC distribution as function of $[\text{Fe}/\text{H}]$ for the whole galaxy can be constructed simply by combining distributions as those of Fig. 1 (typical of different radii), once they had been rescale by means of a suitable function (of time and metallicity) which links the global star formation rate to the globular cluster creation.

In order to plot the different cases on the same scale we normalize each GC-metallicity distribution function by its maximum value. In the upper panel of Figure 3 the shaded histogram represents the innermost population. Our predictions match the data very well, especially in the metal-rich slope and the mean of the distribution. The same happens for the *pure core* populations, which shows how the GCS might be used to probe the CSP in ellipticals. It should be remarked that a second peak centered at super-solar metallicity appears in the distribution predicted by our models, although not evident in the data of the particular radial sub-sample. The lower panel of Figure 3 illustrates model predictions which are more representative of the galaxy as a whole (either at $1R_{\text{eff}}$, i.e. the *intermediate* population, or at several effective radii, the *outermost* population), and we consider them as the fiducial case. These two cases look quite similar to each other and have clear signs of bimodality in remarkable agreement with the spectroscopic data (solid empty histogram, sub-sample of the P06 data with $r \geq R_{\text{eff}}$). A Kolmogorov-Smirnov test returns $>99\%$ probability that both model predictions and observations are drawn from the same parent distribution in the upper panel of Figure 3. The lower panel statistics gives a lower likelihood of 98.4% that both distributions have the same

origin, which is mainly due to the observed excess of metal-poor GCs at large galactocentric radii compared to the model predictions. The prediction of a super-solar metallicity globular cluster sub-population is entirely new and a result of the radially varying and violent formation of the parent galaxy. Moving to the low-metallicity tail, we predict slightly fewer low metallicity objects than expected from observations, which is attributed to the lack of GC accretion from metal-poor satellite galaxies in our model.

In Figure 4 (upper panel) we show the results for a *pure core* GCs, namely one in which we adopt $f_{red}:f_{blue} = 1:0$. In this quite extreme case the observed GCs have been selected with radius $r < 0.5R_{\text{eff}}$. The histogram reflects the shape of a stellar metallicity distribution diagram expected for a typical CSP inhabiting the galactic core. This finding is particularly important, because it might offer the opportunity to resolve the SSPs in ellipticals, at variance with data coming from the integrated spectra which deal with luminosity-weighted quantities. Whereas in Figure 4 (lower panel), the intermediate population is compared to a sub-sample of P06 GCs with $0.5 < r < 1.5R_{\text{eff}}$. This is to show that the multimodality is not an artifact due to the particular radial binning adopted in this paper.

Since the GC populations trace the properties of galactic CSPs in our scenario, we predict an increase of the mean metallicity of the cluster systems with the host galaxy mass, which closely follows the mass-metallicity relation for ellipticals. This has been observed in the GCSs of Virgo cluster early-type galaxies (Peng et al. 2006, ApJ 639, 95). Moreover, we expect that a major fraction of the GCs (i.e. those born inside the galaxy) follows an age-metallicity relationship, in the sense that the older ones are also more α -enhanced and more metal-poor.

Neither a need of an enhanced GC formation during mergers nor a strong role of the accretion of external objects, seems to be required in order to explain the different features of the GC metallicity distributions. Since globular clusters are the closest approximation of a SSP, we expect that this technique will be very helpful to probe the properties of the stellar populations in spheroids, thus avoiding the uncertainties typical of the analysis based on their integrated spectra.

0.4 Concluding remarks

A detailed study of the chemical properties of the CSPs inhabiting elliptical galaxies as well as the change of their properties as a function of both time and radius, allow us to gather a wealth of information. Our main conclusions are:

- Both observed and predicted stellar metallicity distribution for ellipticals show a sharp truncation at high metallicities that, in the light of our models, might be interpreted as the first direct evidence for the occurrence of the galactic wind in spheroids.

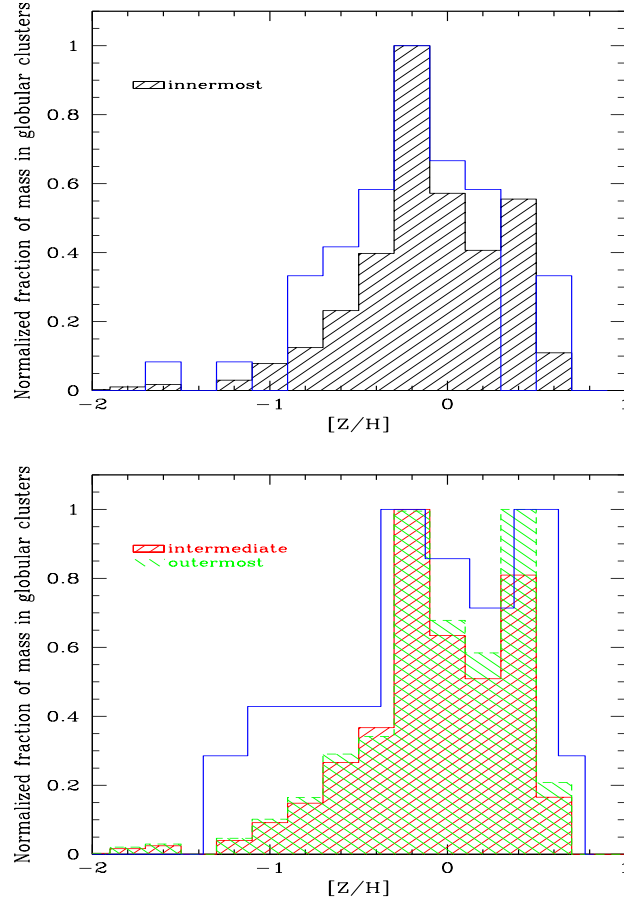


Figure 3: Predicted globular-cluster metallicity distribution by mass as a function of $[Z/H]$ for three different radial compositions. The upper panel shows both model predictions and observations related to the central part of an elliptical galaxy. The lower panel shows the same quantities for cluster populations residing at $r \geq R_{\text{eff}}$. Solid empty histograms: observational data taken as subsamples of the P06 compilation, according to the galactic regions presented in each panel.

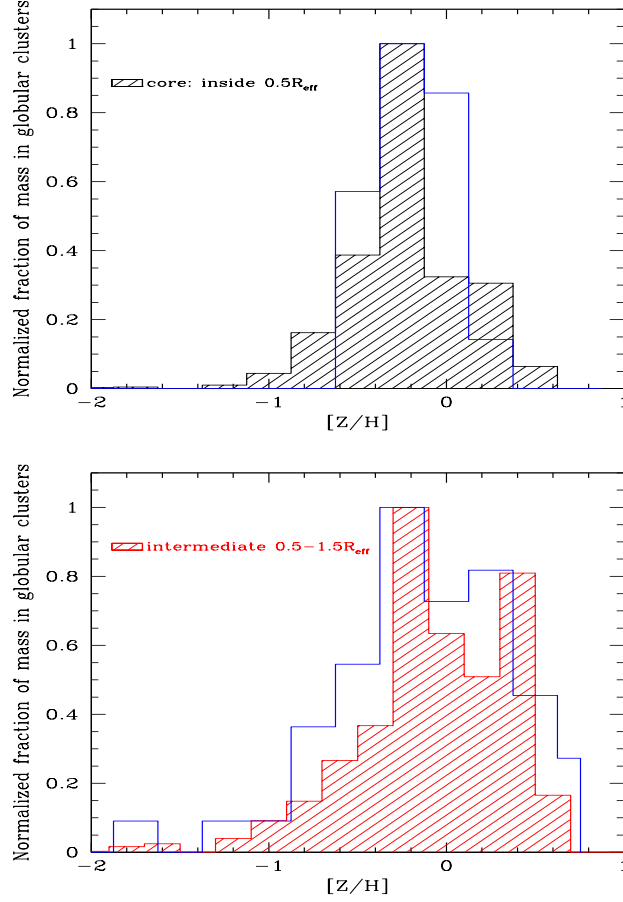


Figure 4: Predicted globular-cluster metallicity distribution by mass as a function of $[Z/H]$ for two different projected galactocentric radii. The upper panel shows both model predictions and observations related to the *pure core* of an elliptical galaxy. The lower panel shows the same quantities for cluster populations residing either at $0.5R_{\text{eff}} < r < 1.5R_{\text{eff}}$. Solid empty histograms: observational data taken as sub-samples of the P06 compilation, according to the galactic regions presented in each panel.

- The stellar component of the most massive and luminous galaxies might attain a metallicity $Z \geq Z_{\odot}$ in only 0.5 Gyr.
- PM04's best model prediction of increasing $[\alpha/\text{Fe}]$ ratio with radius is in very good agreement with the observed gradient in $[\alpha/\text{Fe}]$ of NGC 4697. This strongly suggests an outside-in galaxy formation scenario for elliptical galaxies that show strong gradients (see also Pipino et al. 2007b and ??, this book).
- By comparing the radial trend of $[< Z/H >]$ with the *observed* one, we notice a discrepancy which is due to the fact that a CSP behaves in a different way with respect to a SSP. In particular the predicted gradient of $[< Z/H >]$ is flatter than the observed one at large radii. Therefore, this should be taken into account when estimates for the metallicity of a galaxy are derived from the simple comparison between the observed line-strength index and the predictions for a SSP, a method currently adopted in the literature.
- Abundance ratios such as $[\text{Mg}/\text{Fe}]$ are less affected by the discrepancy between the SSPs and a CSP, since their distribution functions are narrower and more symmetric. Therefore, we stress the importance of such a ratio as the most robust tool to estimate the duration of the galaxy formation process.
- We show that the observed multi-modality in the globular cluster metallicity distributions can be, at least partly, ascribed to the radial variation in the underlying stellar populations in giant elliptical galaxies. In particular, the observed globular cluster systems are consistent with a linear combination of the globular cluster sub-populations inhabiting different galactocentric radii projected on the sky.
- A new prediction of our models, which is in astonishing agreement with the spectroscopic observations, is the presence of a super-solar metallicity mode that seems to emerge in the most massive elliptical galaxies. In smaller objects, instead, this mode disappears quickly with decreasing stellar mass of the host galaxy.
- Since in our scenario the GCs properties sample the galactic CSPs, we predict an increase of the mean metallicity and mean $[\alpha/\text{Fe}]$ of cluster systems with the host galaxy mass, which closely follows the scaling relations for ellipticals. Moreover, we expect that a major fraction of the GCs (i.e. those born inside the galaxy) follows an age-metallicity relationship, in the sense that the older ones are also more α -enhanced and more metal-poor.

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